Optical studies of V4332 Sagittarii - detection of unusually strong KI and NaI lines in emission

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ABSTRACT

We present optical observations of the enigmatic nova-like variable V4332 Sgr. The importance of this object should not be understated since it is considered to be the possible prototype of a new class of eruptive variables. These objects have been the subject of considerable studies at present primarily because of the spectacular eruption of V838 Mon - another member of this class - recently in 2002. The cause of the outburst in such objects is not well understood. Our recent work has shown striking changes in the near-IR spectrum of V4332 Sgr since its 1994 outburst. The optical spectrum presented here confirms that V4332 Sgr is indeed an unusual and extremely interesting object. This spectrum, the first to be taken after a hiatus of nearly 10 years after the outburst, shows several lines in emission but is dominated by exceptionally strong emission in the resonance doublet of KI at 7665 and 7699Å and to a slightly lesser strength in the unresolved NaI doublet at 5890 and 5896Å. The KI lines are shown to be optically thick and considerably broadened. We investigate the site of origin of the KI and NaI emission. Considering the strength of the alkali metal lines - seen at similar strength only in L and T type dwarfs (though in absorption) - we discuss whether the outburst of V4332 Sgr was an explosion on a L or T type dwarf. However $BVRI$ photometry does not support such a scenario but rather shows the central object of V4332 Sgr to be a M-type star with a temperature of 3250K.

Subject headings: stars–novae, cataclysmic variables-stars: individual(V4332 Sagittarii)-techniques: spectroscopic

1. Introduction

V4332 Sagittarii (V4332 Sgr) erupted in 1994 in a nova-like explosion which was recognized to be unusual (Martini et al. 1999). The object showed a rapid post-outburst evolution to a cool M giant/supergiant which was uncharacteristic of a classical nova outburst. The light curve of the object (Martini et al. 1999) showed a slow rise to a maximum visual magnitude of $\sim$ 8.5. This was followed by a fast decline with the decay time for 2 and 3 magnitudes being 8±1 and 12±1 days respectively. Current interest in V4332 Sgr was resurrected by the January 2002 eruption of V838 Mon which showed the outburst characteristics of both objects to be quite similar (Munari et al. 2002). V838 Mon, iconized by its remarkable light-echo (Bond et al. 2003), has been at the center of several, recent and ongoing studies. There is a general consensus that V4332 Sgr, V838 Mon and M31 RV (a red variable that erupted in M31; Rich et al. 1989) may belong to a new and select

class of eruptive variables whose post-outburst behavior is different on many counts from other classes of eruptive variables (Munari et al. 2002; Banerjee & Ashok, 2002). The fundamental question regarding the cause of the explosion in such eruptive variables or quasi-novae is not completely understood. Plausible explanations for the outburst invoke merger of stars (Soker and Tylenda 2003) and a star capturing its encircling planets (Retter and Marom 2003). The cause of the outburst is still uncertain and there is a definite need to study these objects further to gain a better understanding of their nature and evolution.

In a recent work (Banerjee et al. 2003; hereafter BVAL) we had shown that V4332 Sgr has a very interesting near-IR spectrum at present. Several new bands of AlO were detected and it was also shown that the spectral energy distribution (SED) of the object had undergone a striking change - a new dust shell having formed recently. The present optical study shows that V4332 Sgr is rising like a Phoenix from the ashes. Our results, discussed below, show that there is a variety and richness in its spectrum that is rarely encountered in astronomical sources.

2. Observations

The optical observations were made on 29 September 2003 using the recently commissioned 2m Himalaya Chandra Telescope (HCT) located at Hanle, India. Spectroscopy and photometry were done using HFOSC (Himalaya Faint Object Spectrograph Camera) which uses a liquid-nitrogen cooled 2048X4096 pixel CCD with 15 micron square pixels as the detector. It has a $10'$x$10'$ unvignetted field in imaging mode and also has several grisms for low and intermediate resolution spectroscopy. The spectra presented here were obtained at R $\sim$ 870 using a slit $1.3''$ wide. The spectrum of V4332 Sgr and the standard star Feige 110 were obtained with exposure times of 15 and 10 minutes respectively. The standard star spectrum was used to ratio the V4332 Sgr spectrum to remove telluric/air glow lines. The ratioed spectrum was finally multiplied by a smooth polynomial fit to the flux-calibrated spectrum of Feige 110 as given in Massey et al. (1988) - this gives the proper slope to the continuum of the V4332 Sgr spectrum. All spectra were wavelength calibrated using a Fe-Ar spectral lamp.

Photometry in the $BVRI$ bands, using HFOSC, was done by taking multiple exposures in the $BVRI$ bands. Photometric calibration was done by observing the Landolt standard star SA110 - 232 (Landolt 1992). A cross-check for the calibration was also done by calculating the magnitudes of another comparison star SA110 -230. There is a good agreement ($\pm$ 0.05 mag) between the derived and listed magnitudes of the comparison star. The mean air-mass at the time of observations was 1.40 and 2.3 for V4332 Sgr and the standard star respectively. Extinction corrections were done using mean values of the extinction coefficient per unit airmass of 0.209, 0.121, 0.0823 and 0.0498 magnitudes for the B, V, R and I bands respectively for the HCT observatory site. The photometric and spectroscopic data were reduced using IRAF. The details of the photometry and the derived $BVRI$ magnitudes for V4332 Sgr are given in Table 1.

3. Results

3.1. Optical spectroscopy

The spectrum of V4332 Sgr covering the 5000-8300Å spectral range is shown in Figure 1. The identification of the lines and the equivalent widths of the atomic lines are given in Table 2. Some unidentified features are also listed with their observed wavelengths and equivalent widths. As can be seen, the striking feature of the spectrum is the great strength of the KI resonance doublet at 7665 and 7699Å . The blend of the NaI doublet at 5890 and 5896Å, although unresolved in the spectrum, is also very prominent. We have surveyed the literature, as comprehensively as possible, for reported detections of KI and NaI lines in emission. Although their occurrence is not too common (KI detection is much rarer than NaI) they have been seen in a variety of objects viz. comets, Io, Jupiter, the Moon, RCB stars at minimum, a few Be stars like HD 45677, MWC 645 and P-Cygni, around red giants like Betelgeuse and around some N type stars. Among these, RCB stars in particular are seen to display strong NaI lines during their minima (Rao et al. 1999) and KI to a much weaker extent. In general, we find that the observed strength of the KI doublet in V4332 Sgr is unusual and it could be among

the strongest to be detected in an astronomical source. The presence of the RbI lines in emission also appears to be rare. Although the RbI lines are blended with the neighboring TiOγ(3,4) band, we feel their identification is correct because of the good match between their observed and laboratory wavelengths. Several of the TiO bands identified here, are also seen in emission in the peculiar red giant star U Equulei (Barnbaum, Omont, & Morris 1996).

We find that the average full width at half maximum (FWHM) of the KI doublet is greater than that of the instrument profile as obtained from two spectral lamp lines in the same wavelength region. Since gaussian fits to the KI lines and the instrument profile are found to give a good agreement, the intrinsic width of the KI lines can be obtained from

$$FWHM^2_{intrinsic} = FWHM^2_{obs.} - FWHM^2_{instr.} \tag{1}$$

where the subscripts refer to the intrinsic, observed and instrumental widths. For the observed values of $FWHM_{\rm obs.}$ of 10.6Å and $FWHM_{\rm instr.}$ equal to 8.24Å , we find that $FWHM_{\rm intrinsic}$ is $\sim$ 6.6Å or 260 km/s. The expected line width due to Doppler broadening of the KI atoms, having a mass $m_{\rm KI}$, a kinetic temperature T and a turbulent velocity $V_{\rm t}$ (assumed to be gaussian) is given by

$$\Delta\nu_D = \frac{1}{\lambda}\left(\frac{2kT}{m_{KI}} + {V_t}^2\right)^{1/2} \tag{2}$$

From equation 2 it is seen that thermal broadening will account for a negligible amount of the observed line width of 6.6Å (for e.g at $T = 1000$K, the thermal broadening for the KI line is only 1 km/s). Thus there is a large amount of velocity dispersion in the KI emitting gas. A significant part of this broadening could be due to line-of-sight averaging of different velocity components in the KI shell in case it has an expansion or rotation velocity associated with it. This aspect is discussed later in Section 3.3.

The KI doublet lines are expected to have a strength of 2:1 in case they are optically thin. However, the observed ratio is closer to unity for the KI doublet (1.1:1) indicating the lines are optically thick. Following Williams (1994), the optical depth τ in the KI 7665Å line can be calculated from

$$\frac{I_{7665}}{I_{7699}} = \frac{(1-e^{-\tau})}{(1-e^{-\tau/2})} \tag{3}$$

where I_{7665} and I_{7699} are the observed intensities. Considering the observed equivalent widths of 193 and 176Å for the KI lines (Table 2) to represent their intensities, we get a value of $\tau \sim 4.5$ from equation 3.

If the KI emission arises from a column of length R, the column density can then be obtained from the relation

$$\tau = N_{KI}\frac{\sqrt{\pi}e^2}{m_e c}\frac{f}{\Delta\nu_D}R \tag{4}$$

where $N_{\rm KI}$ is the number density of the KI atoms, f is the oscillator strength for the 7665Å transition (f=0.335) and $\Delta\nu_{\rm D}$ is the local line width given by equation 2. Using values of τ = 4.5 and $\Delta\nu_{\rm D}$ = 3.4x10^{11} s^{-1} (corresponding to a intrinsic width of 6.6Å), we derive a column density $N_{\rm KI}R$ = 3x10^{14} cm^{-2}. The value of $N_{\rm KI}R$ can be used to calculate the mass of the KI region (Williams 1994) in case its geometry is better established in any future study - at present we are not too sure of the geometry as discussed in section 3.3.

3.2. Photometry and Spectral Energy Distribution

The SED of V4332 Sgr is shown in Figure 2. The $BVRI$ fluxes have been computed after reddening corrections adopting $E(B-V)$= 0.32 from Martini et al.(1999) and using zero magnitude fluxes from Bessell, Castelli and Plez (1998). The JHK fluxes from BVAL are also plotted to show the SED over an extended wavelength range . The present $BVRI$ data establishes more definitely - as suggested in BVAL - that the hot component of V4332 Sgr is well fit by a blackbody of 3250K. The newly-formed dust component (BVAL) is also well-fitted by a 900K blackbody. Associating the 3250K component with the central star of V4332 Sgr shows that it has an effective temperature corresponding to M5 type. Its luminosity class is uncertain because of distance uncertainties but as per our earlier estimate it is slightly over-luminous

for a main sequence M5 object. The SED also suggests that the central star has remained at a constant temperature of 3250K between the 1998 2MASS observations (BVAL) and now. If this is the quiescent state of the star, then it appears that the 1994 explosion has taken place on a M type star. This gives a more definite classification, not available before, on the likely nature of the progenitor on which the outburst has taken place. This should be an useful input for models investigating the cause of the outburst in quasi-novae. It is difficult to conclude, based on the present data, whether V4332 Sgr is a binary system. The emission lines are in general found to be blue shifted by ~ 3Å - a point already noticed in the high-resolution Hα line profiles of V4332 Sgr obtained during outburst by Martini et al. (1999). The similar observed blueshift of the lines at two different epochs suggests the blueshift of the lines could be due to systemic motion. Radial velocity monitoring at higher spectral resolution (than in the present studies) would be helpful in establishing or ruling out binarity for V4332 Sgr. It may be pointed out that a hot B3V companion to the outbursting star has been reported in V838 Mon (Wagner et al. 2003).

Considering the large strength of the alkali metal lines in V4332 Sgr, we have investigated whether the M5 central object is some variant of a brown dwarf or a very low mass star. Brown dwarfs and very low mass stars show, like V4332 Sgr, very strong resonance lines of the alkali metals - although in absorption (for e.g. Burgasser et al. 2003 and references therein). In these objects, the NaI and KI lines are the strongest while RbI and CsI are progressively weaker (RbI lines are present in our spectrum; the CsI doublet at 8521, 8943Å is not covered in our spectrum). Further evidence that V4332 Sgr type of objects could be related to very cool dwarfs comes from the near-IR spectra of V838 Mon which indicate that it could be a L giant (Evans et al. 2003). We therefore compared the colors of V4332 Sgr with a large sample of L and T type dwarfs whose $BVRIJHK$ magnitudes are available (Dahn et al. 2002). However, our results do not show V4332 Sgr to have the colors of a L or T type dwarf. The $BVRI$ colors of the suggested M5 central star are not red enough. In the near-IR, the comparison is made difficult by the contribution of the dust shell in V4332 Sgr to the JHK colors. While flaring activity on a brown dwarf - over a period of few hours - has been reported (e.g. Rutledge et al. 2002), no instance is known of a nova-like eruption in them.

3.3. Origin and Excitation of the KI emission

Since the KI/NaI lines are seen in emission, and not in absorption, they cannot be of photospheric origin but should originate from an extended envelope. It is likely that some of the emission in the KI/NaI lines could be caused by resonance scattering from the continuum of the 3250K central source. In addition collisional excitation could also contribute to the observed line strength. This is because the resonance lines have low excitation energies viz. they are at 2.1ev, 1.61ev and 1.56ev above the ground level for NaI, KI and RbI respectively. Collisions in a low temperature gas could excite the atoms to the upper levels. Further, the work of Tsuji (1973) on expected molecular abundances of different species in stellar atmospheres shows that the alkali metals do not associate themselves into any molecular form at low temperatures in the range 1000-1500K. Thus the availability of large number of neutral atoms with low energy for their excitation could be responsible for the strong KI and NaI lines. However, we have presented here only a qualitative discussion and an estimate of the fractional contribution of collisional excitation vis-a-vis resonance scattering to the observed line strengths needs a detailed analysis.

As the KI/NaI lines are optically thick, yet do not show P-Cygni profiles, they are unlikely to originate in a stellar wind. Two possibililities for the site of the KI emission are i) a disc around the central source or ii) the ejecta of the 1994 outburst. A point in support of the latter case is that NaI was seen in emission in the ejecta during the 1994 outburst (Martini et al 1999). However, the 1994 ejecta is expected to have a spatially resolved diameter of $2''$ to $3''$ based on the well-estimated expansion velocity of 200 - 300 km/s for the ejecta and an adopted distance estimate of 300pc to the object (Martini et al. 1999). The present optical spectrum, suggests weakly that there could be extended emission along the slit at the positions of the KI and NaI lines. A high spatial resolution image of V4332 Sgr would be invaluable to look for extended emission zone around the object. It

may be pointed out that the observed broadening of the KI lines could be accounted for by an expanding nova shell.

However, we favor the possibility of the KI gas being in an extended disc around V4332 Sgr. In a recent observation from UKIRT, we have detected the ^{12}CO fundamental band at 4.67 μm strongly in emission (again a rare phenomenon) and also find a deep water ice absorption band at 3.1 microns (paper under preparation). The co-existence of several species, requiring successively cooler temperature conditions, in the same object viz. neutral species like KI/NaI, molecular species as AlO, TiO and CO and finally a cold, solid-phase water ice component suggests a spatial stratification of the different species. Therefore, a possible and simplistic scenario for the geometry of V4332 could be a central source at 3250K surrounded by a dust shell. The dust shell is either clumpy or optically thin since radiation from the central source is seen in the SED. Surrounding the central source is a disc with the atomic and molecular species in the inner parts and ice in the colder, outer regions. If the gas in the disc has a Keplerian velocity (which would typically be $\sim$ 150 km/s for a M5 star at a distance of 5-10R_{*}), the emission lines from the disc could get broadened substantially due to rotational motion. This could account for the observed width of the KI lines in V4332 Sgr. Incidentally the presence of a disc, if it has planetary bodies in it, creates the necessary background for the outburst mechanism of a star capturing its planets - as suggested by Retter and Marom (2003)- to become viable.

This work highlights the detection of strong emission lines of alkali metals in V4332 Sgr. The optical spectrum strengthens the idea - since nothing similar to it has been found earlier in a nova - that V4332 Sgr belongs to a new class of eruptive variables. V4332 Sgr is found to be an extremely interesting object, worthy of wider attention and studies.

The research work at PRL is funded by the Department of Space, Government of India. We thank the staff of HCT, Hanle and CREST, Hosakote, that made these observations possible. We are grateful to the referee, M. Della Valle, for his helpful comments.

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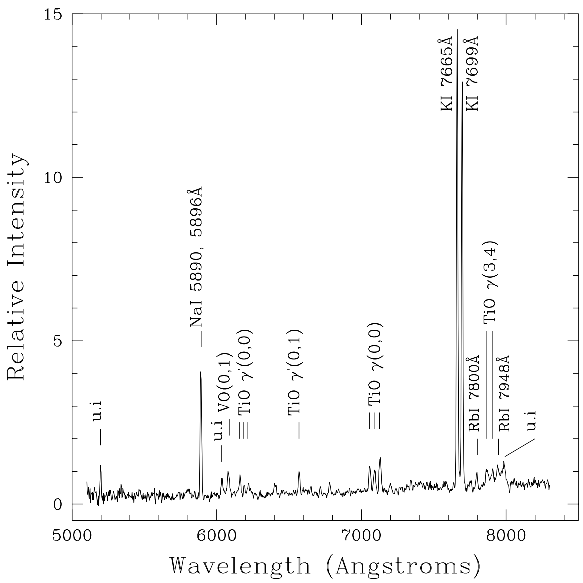

Fig. 1.— The observed optical spectra of V4332 Sgr showing the unusually strong KI resonance doublet at 7665 and 7699Å and the unresolved NaI resonance doublet at 5890 and 5896Å. The identification of the other prominent lines, as given in Table 1, are marked (u.i means unidentified).

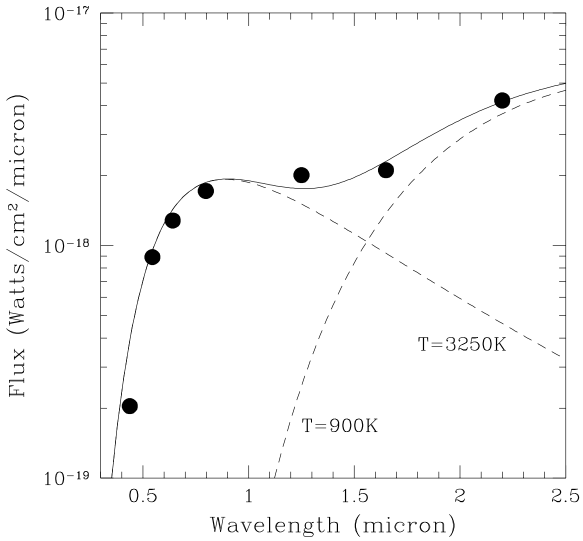

Fig. 2.— The SED of V4332 Sgr covering the optical and near-IR range. It is found to be well fitted (bold line) by the sum of 2 black-bodies (dashed lines) viz. a hot component at T = 3250K and a colder dust component at 900K.

Table 1: Log of photometric observations for 29 Sept. 2003

UT	Band	Exposure Time(s)	Integration Time(s)	Mag. (error)
12.199	B	50	250	20.04 (0.15)
12.017	V	10	90	17.52 (0.14)
11.955	R	4	80	16.31 (0.01)
11.955	I	4	80	15.01 (0.03)

Table 2: A list of the observed lines in V4332 Sgr. Unidentified lines are marked as u.i and uncertain identifications with a question mark.

S.No	Rest Wave-length(Å)	Species	Eq. Width (Å)
1	5197	u.i	40
2	5890,96	NaI	210
3	6035	u.i	15
4	6086.4	VO (0,1)?	
5	6159	TiO $\gamma'(0,0)$	
	6187	”	
	6215	”	
6	6403	u.i	16
7	6569	TiO $\gamma'(0,1)$?	
8	6651.5	TiO $\gamma'(1,0)$	
	6681.1	”	
	6714.4	”	
9	6780	u.i	15
10	6843	u.i	4
11	7054.5	TiO $\gamma(0,0)$	
	7087.9	”	
	7125.6	”	
12	7197.7	TiO $\gamma'(1,1)$	
13	7664.9	KI	193
	7698.96	KI	176
14	7800.3	RbI	9
15	7861	TiO $\gamma(3,4)$	
	7907.3	”	
13	7947.6	RbI	5
14	7987	u.i	6